Comparisons of Radiative Transfer Models of Vegetation Canopies With Laboratory Measurements

Alan H. Strahler[1] and Shunlin Liang[2]

[1]Dept. of Geography, Boston University
675 Commonwealth Ave., Boston, MA, 02215.
Phone: 617-353-5984; Fax: 617-353-3200; Internet: alan@bu.edu

[2]Dept. of Geography, University of Maryland
Lefrak Hall, College Park, MD, 20742.
Phone: 301-405-4070; Fax: 301-314-9299; Internet: sliang@eng.umd.edu

ABSTRACT

Laboratory measurements of the directional reflectance of three young crop canopies canopies fit radiative-transfer-based plane-parallel models with good accuracy. The measurements were collected at a unique facility in Changchun, China, using an apparatus that simulates solar radiation at zenith angles up to 45° on a 1-m diameter target. A curved arm fitted with multiband radiometers revolves on a circular track around the target, allowing rapid measurement of multispectral bidirectional reflectance factors of the target at 10°-zenith and azimuth angle increments. Because the measurements are made under controlled conditions, effects of such confounding factors as wind and diffuse (sky) irradiance can be avoided. Three one-dimensional radiative-transfer canopy reflectance models were compared to the bidirectional reflectance measurements in the infrared wavelength region, in which multiple scattering treatments differentiate the three models. The models generally fitted the data for young wheat and corn canopies well, with some departures for a young soybean canopy. The escape of multiply-scattered radiation from the sides of the canopy in the case of soybeans and corn produced some deviations from modeled results.

INTRODUCTION

In recent years, a number of mathematical models have been devised to describe the directional scattering behavior of leaf canopies. Approaches to modeling have varied from geometric optics (Li and Strahler, 1986, 1992), in which the vegetation canopy is taken as a collection of three-dimensional plant crowns that cast shadows on each other and on the background, to radiative transfer (Goel, 1988; Myneni et. al, 1990), in which the vegetation is taken as a volume-scattering medium of finite scattering elements. The abundance of models, however, has not kept pace with the acquisition of data to validate them. Only a limited number of datasets are available that provide both radiance measurements and independent measurements of the physical parameters driving the reflectance models.

This paper describes a laboratory facility located in the Peoples' Republic of China that provides for the acquisition of directional reflectance measurements of plant canopies under controlled conditions. Laboratory measurement of directional reflectance has several distinct advantages over field measurements. First, by using a single collimated light source, irradiance can be restricted to direct beam only, eliminating the effects of diffuse radiation that are present in field measurements. Second, the effects of wind are also eliminated, allowing accurate measurement of leaf angle distribution. A third advantage is that the position of the source of irradiance in the hemisphere can be fixed in position. Outdoors, the sun constantly changes angular position in the sky, which may be a problem if the period of acquisition of directional radiance measurements is protracted. The disadvantage of the laboratory approach lies primarily in that there are practical limits to the size of the target. For the facility described here, the sample stage is of one meter diameter, and so is most suited to observations of young and/or small plants.

LABORATORY MEASUREMENTS

The directional reflectance measurements described in this paper were acquired at the Solar Simulation Laboratory for the Measurement of Bidirectional Reflectance, a facility of the Changchun Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, located in the city of Changchun, Jilin Province, Peoples' Republic of China. The laboratory is further affiliated with the Jinguetan Remote Sensing Test Site, which is also a facility of the Chinese Academy of Science.

Laboratory Apparatus

Figure 1 provides a sketch of the laboratory apparatus used for acquisition of directional measurements. The light source is a carbon arc lamp that simulates the solar spectrum, positioned above and to the side of the target. A collimating lens delivers a

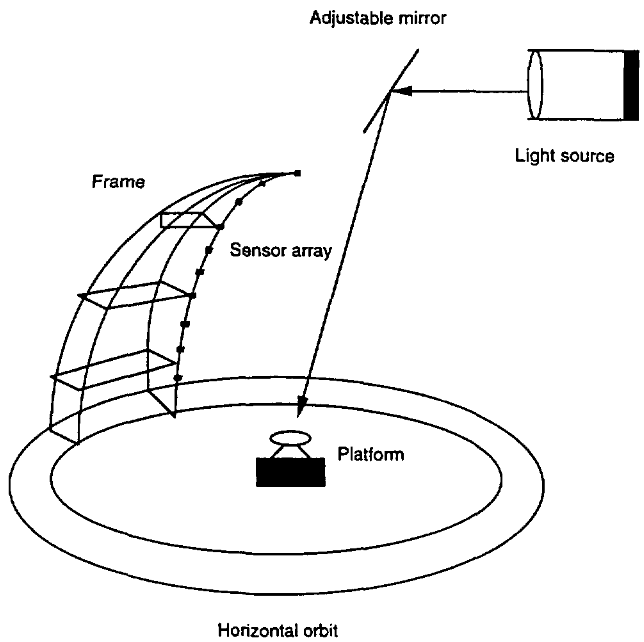

Figure 1.
Illustration of the measurement apparatus in the simulation laboratory.

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horizontal beam of illumination, which is directed onto the target by an optical mirror. By varying the position and angle of the mirror, the solar simulation beam can be directed at the target at any zenith angle between nadir and 45°. Power output is variable from 4000 to 25,000 w, providing target irradiance at a value between 0.3-0.7 times the solar constant. The target is a movable stage that can raised and lowered on an electric motor drive.

Radiance measurements are acquired by radiometers mounted on a curved frame that maintains a uniform distance of 3 m from the target. The radiometers are positioned at 10° view zenith angle increments from nadir to 90°. The frame rotates around the target on a circular track, acquiring data at 10° increments of azimuth angle. Each radiometer makes simultaneous measurements in six spectral wavebands. A single series of measurements thus provides 2160 observations of radiance. However, with a planar surface target such as a vegetation canopy, the field of view at zenith angles of 80° and 90° exceeds the bounds of the target. Accordingly, these measurements are normally discarded for our application, yielding datasets of 1776 measurements. Data acquisition is controlled by a microcomputer system that moves the irradiance mirror and then starts the radiometer arm assembly in motion on its circular track. Magnetic switches embedded along the track trigger the acquisition of radiometric data. A full measurement cycle requires about ten minutes, which includes returning the radiometer frame to its starting position and moving the mirror to simulate a new solar zenith angle.

Experimental Procedure

The plants comprising each canopy were grown from seed outdoors under natural conditions. They were planted in sturdy wire frame boxes measuring 0.25 by 1.0 m and about 0.35 m deep. The open frames permitted normal root growth. For each experiment, four boxes were placed on the target, providing a canopy with an area of 1 sq m. Radiometric measurements of the canopy were then acquired at specified irradiance angles. After radiometric measurements, each canopy was destructively sampled to determine mean leaf area, leaf height, and leaf angle distribution. Leaf reflectance and transmittance were determined from a small sample of leaves using a spectrometer.

Following the stripping of the leaves from the plants, additional sets of radiometer measurements were made to measure the reflectance of stems and soil. For the canopies studied, radiometeric measurements of the stem canopy and the bare soil surface were not distinguishable.

CANOPY RADIATIVE TRANSFER MODELS

The measurements made at the Solar Simulation Laboratory were compared to the predictions of three different but related models of vegetation canopy bidirectional reflectance that utilize principles of radiative transfer. These are the Gauss-Seidel numerical model (Liang and Strahler, 1993a); the asymptotic fitting model (Liang and Strahler, 1993b); and the four-stream model (Liang and Strahler, 1994). The Gauss-Seidel numerical model uses Gauss-Seidel iteration to solve the radiative transfer equation for a coupled atmosphere and canopy medium that is homogeneous in the plane. The medium is divided into a large number of layers, each with a small optical depth, and the radiative transfer equation is solved in each layer successively and iteratively. Cycling continues until a stable solution is reached. The asymptotic fitting model (Liang and Strahler, 1993b) uses the well-known solution of Van de Hulst (1980) to the radiative transfer equation for a semiinfinite medium with an arbitrary phase function. It is modified for soil reflectance using a relation from King (1987). In the four-stream model, an analytical solution is derived for a plane-parallel canopy medium in which the multiple scattering radiation field is restricted to four streams that are taken at Gaussian quadrature points (Liang and Strahler, 1994).

Table 1. *Biophysical parameters of crop canopies*

Parameter	Wheat	Soybean	Corn
Leaf reflectance, r_l	0.43	0.52	0.48
Leaf transmittance, t_l	0.33	0.41	0.40
Soil reflectance, R_s	0.073	0.073	0.053
Leaf area index, LAI	1.80	1.41	8.04
Leaf angle distribution, u	1.148	1.979	1.772
Leaf angle distribution, v	2.646	1.363	2.569
Hotspot parameter, K	0.0	0.0	0.0
Wax refractive index parameter, n	1.35	1.35	1.45

DATA ANALYSIS

Although more extensive analyses of reflectance measurements acquired at the Solar Simulation Laboratory have been made, we report here only a limited set that is selected for validation of the three candidate models described above. Since the three models differ primarily in how they approximate multiple scattering, we present only data and model runs from the near infrared (0.76-0.90 μm) where multiple scattering within the leaf canopy will be large. Due to a detector malfunction, data acquired by the nadir-viewing radiometer in this band were not available. Note also that for these model runs we have assumed isotropic soil reflectance with a value integrated from bare-soil observations. This is because the asymptotic model does not provide for an anisotropically-reflecting soil layer, and using an isotropic lower bound for all three models allows them to be compared more directly.

Results are presented for three crop canopies: wheat, soybean, and corn. Table 1 provides a list of the biophysical parameters used in the model runs. Leaf reflectance and transmittance were determined by a spectrometer providing monochromatic illumination and measurement at fixed angles. An apparatus utilizing an integrating sphere was not available. As a result, we adjusted the values for these parameters somewhat. The leaf angle distributions were fit by a two-parameter beta distribution (Goel and Strebel, 1984) with values as shown in Table 1. The wheat canopy was most erectophile, followed by the corn canopy. The soybean canopy was strongly planophile.

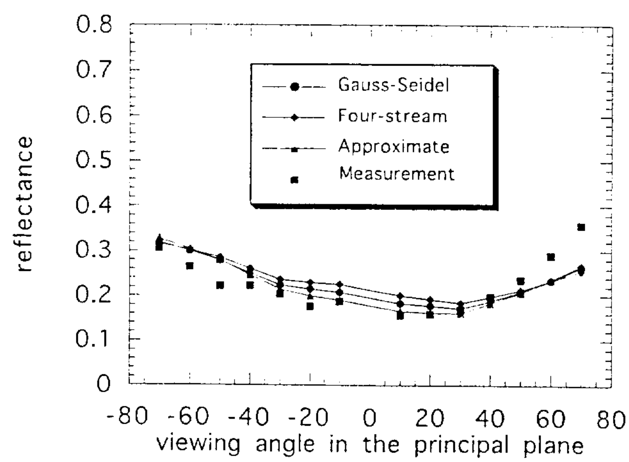


Figure 2.
Comparison of observed and modeled reflectance values for a young wheat canopy in the principal plane. Solar zenith angle is 30°.

Figure 3.
Comparison of observed and modeled reflectance values for a young soybean canopy in the principal plane. Solar zenith angle is 30°.

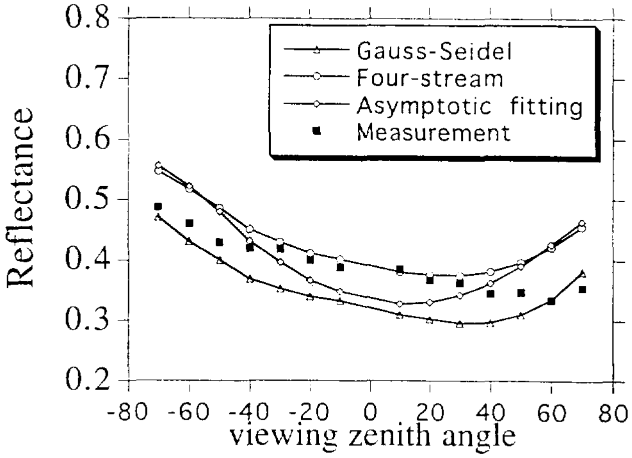
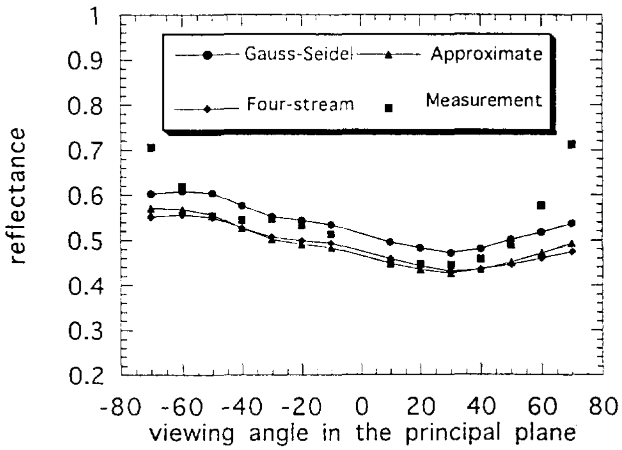


Figure 4.
Comparison of observed and modeled reflectance values for a young corn canopy in the principal plane. Solar zenith angle is 30°.



For the wheat canopy, shown at a 30° solar zenith angle in Figure 2, all three models predict more-or-less similar angular reflectances, although there is some difference among them in the nadir portion of the scan. The young canopy, consisting of shoots with largely vertical leaves, shows a reasonably good fit to the models, especially at lower view zenith angles. However, as illumination angle increases, the canopy shows an increasing brightness trend in the forward scattering direction that is not predicted by the models. We may speculate that the discrepancy is due to the assumption of isotropic soil reflectance, since the soil appeared to the observer at the time of measurement to have an enhanced brightness in the forward scattering direction.

The soybean canopy consisted of relatively small plants, exhibiting a leaf area idex of only 1.41. Row effects were still visible, so the canopy was oriented with the principal plane across the rows. Figure 3 compares the measurements with model calculations for the soybean canopy at a solar zenith angle of 30°. Canopy reflectance shows a consistent trend toward somewhat elevated values at near-nadir zenith angles (±20°), perhaps due to the near-planophile leaf orientation. This effect is not well predicted by the models, although the Gauss-Seidel model does show a slight increase in this range. The models also predict a significant increase in reflectance with view zeniths in the forward scattering direction, a phenomenon that is marked in the data only by an increase in reflectance at the 70° point. Among the three models, the Gauss-Seidel shows the lowest values. Since it provides the most exact solution to the radiative transfer equation, the discrepancy points out the limitations of analytical solutions under these conditions.

The corn canopy consisted of older, taller plants over a natural soil background, exhibiting a leaf area index of about 8. At this LAI, multiple scattering is very strong (Figure 4). The Gauss-Seidel solution shows a slightly higher reflectance than the two approximation methods. The measured canopy reflectance is somewhat lower, presumably due to the escape of scattered radiation from the sides of the canopy. In general, the shape of the observed reflectance curve matches the models well at low and intermediate zenith angles. However, canopy reflectance increases sharply at the extremes.

CONCLUSIONS

Laboratory simulations can be very useful tools in validating canopy reflectance models, since such factors as diffuse irradiance and wind are eliminated in the laboratory setting. A series of laboratory measurements of the directional infrared reflectance of young wheat, soybean, and corn canopies shows that radiative transfer models can predict canopy reflectance with reasonable accuracy. The analysis also calls attention to the conditions of high multiple scattering under which approximate models may give unsatisfactory results. Some difficulties in measurement that arise from the finite nature of the canopy sample can possibly be overcome in future experiments by restricting the field of view of the radiometers or by moving to three-dimensional canopy models that better fit the scene as measured.

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